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Constant depth scoring of fibre reinforced plastic structures to prevent delamination

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Abstract

Scoring of the outer layers of a workpiece with small engagement (a_e) using circular saws is a well known method to avoid unwanted delamination of these layers, such as coatings of wooden particle boards. In edge milling fibre reinforced plastics (FRP), delamination also occurs in the top or bottom layer of the component and requires time intensive rework or scrapping of material. A combined process of scoring and milling is presented in this paper as a means to avoid delamination during machining of FRP structures such as aircraft carbon FRP parts. For the scoring process a diamond electroplated circular wheel is used. To guarantee a constant width of the scored slot, a constant depth of engagement is needed due to the shape of the grinding wheel. Therefore the profile of the scoring path on the workpiece surface is measured with respect to the machine coordinate system to correct a variation in the workpiece thickness and to compensate for uneven clamping. Next, the workpiece is scored with constant depth of engagement ($a_{e,s} < 0.5$ mm) and a high feed velocity of up to 16 m/min. Subsequently, the scored component is machined with a conventional polycrystalline diamond (PCD) milling tool. From experiments it is proven that a delamination-free edge is achievable even with a worn tool (cutting edge radius $r_n > 50$ μ m) at an increased feed velocity ($v_{f,m} = 4.5$ m/min). Without scoring, flawed workpiece edges have been obtained with cutting edge radii beyond $r_n > 23$ μ m (progressive uniform wear stage) and a feed velocity of $v_{f,m} = 1.5$ m/min. Hence, high performance cutting (HPC) edge milling of composites may be realized by an initial scoring step to fulfil quality requirements of the machined edges and simultaneously increase the tool life of the milling tool.

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1. Introduction

Delamination of the workpiece material of fibre reinforced plastic (FRP) is a common problem during machining. Delamination is the failure between layers of a laminate which results in protrusions of fibres and fibre bundles at the machined edge [1, 2]. Wood and FRP are both fibre reinforced materials; therefore many methods and processes are applicable to both materials. In the wood industry scoring is a well established process to avoid delamination or chipping of wooden particle boards or solid wood [3]. Scoring is the machining of the top layer of a component, preferably with a small constant engagement $a_{e,s}$. Thus, scoring is a promising approach in

FRP machining for reliable complying with the edge quality requirements at elevated feed velocity, i.e. under high performance cutting (HPC) conditions.

Delamination heavily depends on the wear stage of the tool and is unpredictable due to the diversity of material/tool combinations. FRP machining processes are therefore difficult to automate. Poor edge quality leads to manually conducted, time intensive rework. Especially delamination of carbon fibre reinforced plastic (CFRP) parts in aerospace industry is reduced constructively by applying top layers of glass fibre reinforced plastic (GFRP) weave. Unfortunately such layers increase the workpiece weight and cost. Recent research shows that delamination

can be reduced for some applications by favourable milling trajectories [1].

The occurrence of delamination has been investigated in [1, 4]. As presented in [4], the fibres of the outer layer initially delaminate and delamination propagates. The main reason for delamination is interlaminar shear stress and in some cases peeling stress that is induced by active forces F_a on the cutting face. If the compressive stress transverse to the fibre direction is greater than the shear stress in the laminate plane, interlaminar failure of the laminate occurs. This is described in the failure criterion for interlaminar stress according to Modus C [2]. The boundary zone around the machined surface that is damaged by delamination can be calculated from measured forces. It has been shown that the outer layers of a component preferentially delaminate due to the lack of support [5, 6].

FRP is an anisotropic material and its material constants vary with the orientation of the fibres. For description purposes, multiple angles are introduced to refer to operands and measurands. The tool engagement angle φ describes the current angle of the cutting edge and starts for straight slot milling at $\varphi_s = 0^\circ$ and ends at $\varphi_e = 180^\circ$. The fibre orientation angle ϕ is defined as the counter clockwise angle between the feed direction and the fibre. The fibre cutting angle Θ is defined as the counter clockwise angle between the current cutting direction of the engaged cutting edge and the fibre [4].

It has been shown by [6, 7] and our own experiments that delamination may be avoided by a sharp cutting edge that leads to low active forces (Sec. 3).

Alternatively, a small engagement (e.g. subsequent finishing after rough machining) lowers the active forces which can be explained by the force model mentioned by [8] and [9]. Their approach for cutting force F_c and cutting perpendicular force F_{cN} induced by one cutting edge is based on a function of the axial depth of cut $a_{p,m}$ and instantaneous chip thickness h which is a function of feed f and the tool engagement angle φ .

$$\begin{bmatrix} F_c \\ F_{cN} \end{bmatrix} = a_{p,m} \left(h \begin{bmatrix} K_{tc}(\Theta) \\ K_{rc}(\Theta) \end{bmatrix} + \begin{bmatrix} K_{te}(\Theta) \\ K_{re}(\Theta) \end{bmatrix} \right) \quad (1)$$

with $h(\varphi, f) = f \sin \varphi$

The resulting force consists of one part to account for the material cutting which changes with the chip thickness $h(\varphi, f)$, and a second part to account for the forces due to friction and elastic resilience. The coefficients K_{tc} and K_{rc} represent the materials resistance to machining in the tangential and radial directions and determine the cutting force, whereas the coefficients K_{te} and K_{re} are introduced to determine the rubbing force. The material coefficients are functions of the current fibre cutting angle Θ . For common applications, h is constant along the material thickness t_w and the forces are equally distributed along the material thickness.

Finally it has been proven by [4] that delamination and progressive delamination occurs under fibre cutting angles between 90° and 180° . Fibres that are cut first at critical

fibre cutting angles Θ might initially delaminate and propagate into uncritical ranges of Θ after initial delamination. The results are consistent with the findings of [9], who demonstrates that the specific cutting forces K_{rc} and K_{tc} in critical angle areas are relatively higher than in non-critical areas.

Nomenclature

α	angle on the circumference of the grinding tool [°]
γ_p	back rake angle of the milling tool [°]
Θ	fibre cutting angle [°]
φ	tool engagement angle [°]
ϕ	fibre orientation angle [°]
$a_{e,s}$	engagement of the grinding tool [mm]
$a_{e,m}$	engagement of the milling tool [mm]
$a_{p,m}$	depth of cut for the milling tool [mm]
d_d	delamination depth [μ m]
d_{gr}	depth of the groove [μ m]
d_m	diameter of the milling tool [mm]
e	exit points of the cutting edge of the milling tool at the upper layer [1]
f_z	feed per tooth for the milling tool [mm]
F_c	force in feed direction of the milling tool [N]
F_{cN}	force in feed normal direction of the milling tool [N]
F_a	active force [N]
h	chip thickness [mm]
K_{tc}	cutting force coefficient in tang. direction [N/mm ²]
K_{rc}	cutting force coefficient in rad. direction [N/mm ²]
K_{te}	rubbing force coefficient in tang. direction [N/mm ²]
K_{re}	rubbing force coefficient in rad. direction [N/mm ²]
l_f	length of milling path [mm]
r_n	rounded cutting edge radius [μ m]
t_w	workpiece thickness [mm]
$v_{f,p}$	feed velocity for profile measurement [m/min]
$v_{f,s}$	feed velocity for scoring [m/min]
$v_{f,m}$	feed velocity for milling [m/min]
$v_{c,s}$	cutting velocity for scoring [m/min]
$v_{c,m}$	cutting velocity for milling [m/min]
w_s	width of the scored slot [mm]
z	coordinate along material thickness direction [mm]

2. Theory of delamination extended for scored surfaces

By scoring a v-shaped groove is machined into the top layer of the component. This groove disrupts the delamination propagation along the fibre direction. To guarantee this disruption of delamination propagation the depth of the groove d_{gr} ($\approx a_{e,s}$) must be greater than the depth of the delaminating fibres d_d (Fig. 1A). Common CFRP laminate layers have a thickness of about 0.25 mm whereas single fibre thickness is about 5 μ m [2].

Since mostly the outermost laminate layers are prone to delaminate, a groove depth between 0.2 - 0.5 mm is normally sufficient. In case the groove's depth d_{gr} is too low, the delamination propagation will continue below the groove (Fig. 1B).

$$h = \begin{cases} 0 & \text{for } 0 \leq z < z_1 \\ f \sin \varphi \frac{z - z_1}{z_2 - z_1} & \text{for } z_1 \leq z < z_2 \\ f \sin \varphi & \text{for } z_2 \leq z \leq t_w \end{cases} \quad (2)$$

$$z_1 = \frac{d_m/2 (1 - \cos(180^\circ - \varphi)) - f \sin \varphi \cos(180^\circ - \varphi)}{\tan \alpha/2}$$

with

$$z_2 = \frac{d_m/2 (1 - \cos(180^\circ - \varphi))}{\tan \alpha/2}$$

for $180^\circ - \arccos\left(\frac{d_m - w_s}{d_m}\right) < \varphi < 180^\circ$

Fig. 2 describes a milling tool in full engagement (workpiece on the right) for different fibre orientation angles ϕ . The critical fibre cutting angles $90^\circ < \Theta < 180^\circ$ are marked by the red and yellow areas. Considering the interruption provided by the groove, the critical area is reduced to the red areas where the cutting edge engages the slope of the groove on the side of the workpiece.

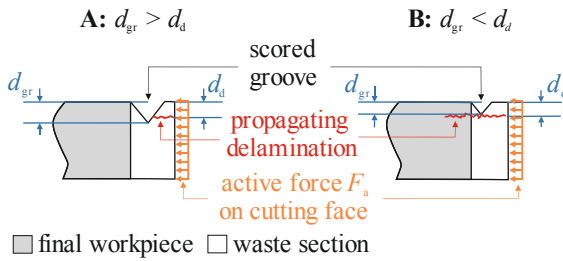


Fig. 1. Delamination propagation ($d_{gr} < d_d$) and interruption ($d_{gr} > d_d$) at a groove

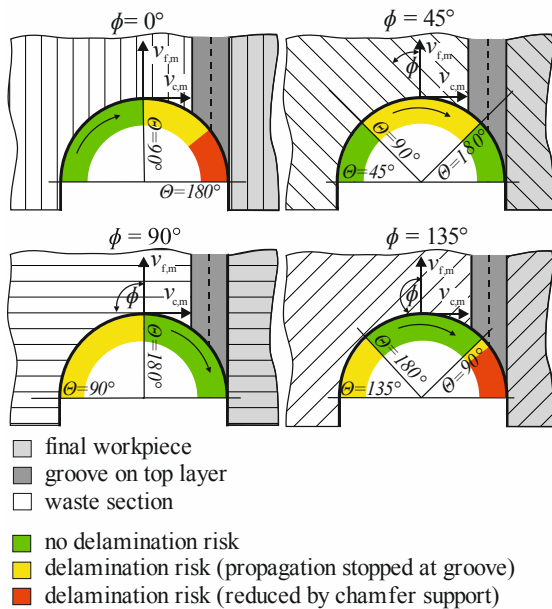


Fig. 2. Areas of initial delamination

Four situations are possible (Fig. 3A - D). By modifying the definition of h as a function of φ, f_z and a coordinate z in the direction of the material thickness t_w , the chip thickness h can be calculated for a distinct z -position along the cutting face.

For the presented case of down milling the scored workpiece edge, h is defined along material thickness z by equation 2. It is assumed that an ideal v-shaped groove with an angle α is present.

As the cutting edge engages the workpiece with increasing φ , the chip thickness h increases until it reaches its maximum of $h(90^\circ) = f_z$ (Fig. 3A).

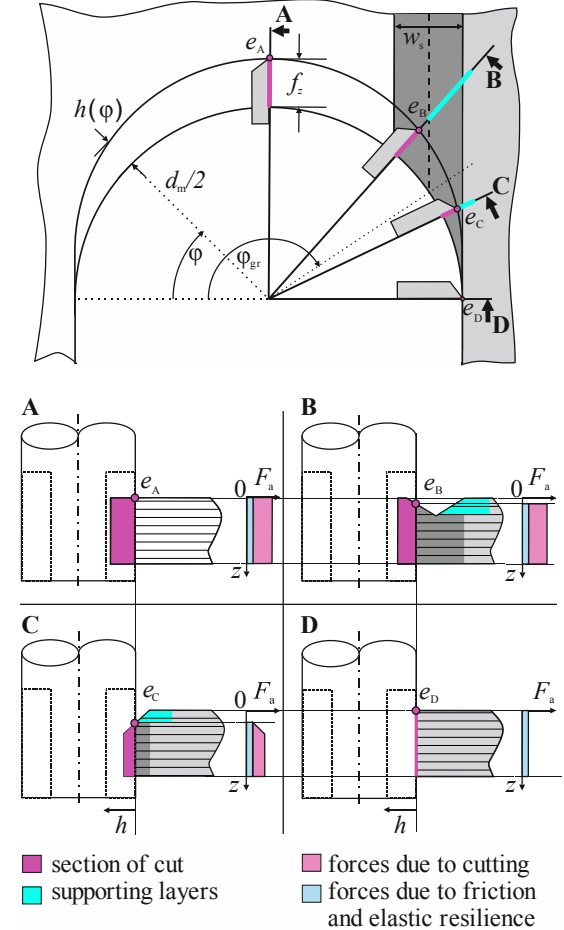


Fig. 3. Four stages during engagement in a pre-scored workpiece

This implies a corresponding load distribution profile of the force along the material thickness z (illustrated to the right of each drawing). With further increasing φ the cutting edge approaches the groove (Fig. 3B). Positions A and B are either located in the green or yellow area depending on the fibre orientation angle. If delamination occurs in these positions, it will proceed either to the waste part (left side) or towards the workpiece where it is stopped by the scored groove. When the cutting edge proceeds from position B to C the chip thickness h is decreasing and the point where the

cutting edge exits the workpiece on the upper side e moves on the left slope of the groove until the cutting edge reaches the bottom of the scored groove at $\varphi_{gr} = \arccos[1 - w_s/d_m]$. The cutting edge then proceeds to position C with further decreasing h and point e moving on the right slope of the groove upwards. The chip thickness h at the exit point e_c is zero (eq. 2). The material of the upward slope to the right of point e_c is present to support the upper layer against delamination (Fig. 3C cyan). When the cutting edge reaches position D, h is zero and forces consist only of friction and elastic resilience.

3. Experimental setup

Experiments were conducted on a 5-axis CNC machine (Reichenbacher Vision II Sprint) with a Siemens 840 Di controller. The machine is equipped with a dust extraction system suitable for fibre reinforced plastic materials. For the tests carbon fibre reinforced plastic (CFRP) material with a thickness of $t_w = 6.2$ mm was used. It was composed of:

- HTS fibre (65%)
- 6376 matrix resin
- $[0_1/90_2/0_2/90_2/0_2/90_2/0_1/0-90$ plain weave₁₀/0-90 GFRP plain weave₁]

In the tests the unidirectional layer was on the top and the weave layer was on the bottom. The experiments were divided into two cases; straight edge milling ($l_f = 250$ mm) and milling of circular holes ($d = 50$ mm).

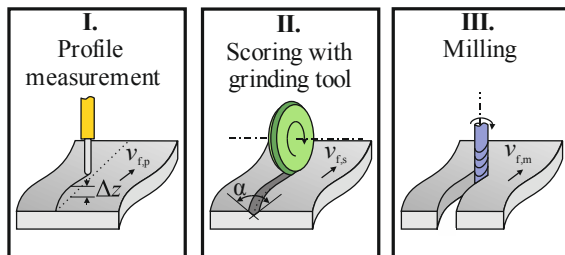


Fig. 4. Constant depth scoring of fibre reinforced plastic structures

The process was divided into three steps (see Fig. 4). First the actual height of the profile to be scored was measured with an inductive gauge that was connected to a measurement computer by a signal conditioning device. The gauge was oriented parallel to the spindle axis and was led along the milling path with a feed velocity v_{fp} of 8 m/min. By interpolation of the measured data a path correction was calculated that was added to the proposed path of the CNC-program. For the process of circular holes machining a conventional electronic measuring sensor was used. For each hole to be pre-scored nine points were measured; the centre and 45° points around the centre on a diameter of 50 mm. As a second process the contour on the upper layer of the workpiece was scored with the grinding tool with small engagement, which was mounted to the motor spindle by a crosshead.

To calculate the width of the scored slot for path correction orthogonal to the feed direction in the workpiece plane, the following equation applies:

$$w_s = 2 a_{e,s} \tan \frac{\alpha}{2} \quad (3)$$

In this equation, $a_{e,s}$ is the engagement and α is the tip angle of the grinding tool at its circumference. The electroplated diamond grinding wheel (D427) has a tip angle $\alpha = 90^\circ$ (Fig. 5A). The main reason an angle of 90° was chosen is that if by error a chamfer remains after milling it has a technical common angle of 45° . The cutting speed $v_{c,s}$ was set to 35 m/s and the feed rate $v_{f,s}$ to 16 m/min. Hence, keeping in mind usual feed velocities for machining such materials of $v_{f,m} = 2$ m/min the overall machining time will only slightly increase in consequence of these additional steps.

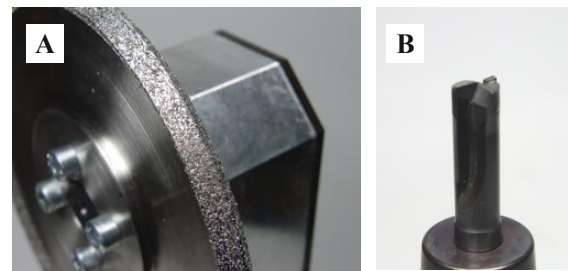


Fig. 5. Diamond electroplated scoring tool and post-scoring milling tool

The third step was the milling with a PCD tool with two cutting edges (Fig. 5B) of a diameter $d_m = 10$ mm and a back rake angle $\gamma_p = 0^\circ$. Depth of cut was $a_p = t_w$. In order to obtain a high productivity, the feed velocities $v_{f,m} = 1.5$ m/min corresponding to usual conditions of industry, 3 m/min and 4.5 m/min were investigated; the cutting velocity $v_{c,m}$ was set to 754 m/min. Three tools with different initial rounded cutting edge radii r_n (in the stage of progressive uniform wear [10]) were chosen (sharp $r_n \approx 7$ μm, semi worn $r_n \approx 25$ μm and worn $r_n \approx 55$ μm). The cutting edge radius was measured with a micro-coordinate measurement system (Alicona InfiniteFocus).

Forces on the workpiece were measured with a Kistler multicomponent force plate Type 9281B connected to a Kistler Type 5019 Charge Amplifier and a National Instruments PCI Data Acquisition Box.

The resulting quality of the machined edges was documented by using a microscope (Olympus SZX10) and the micro-coordinate measurement system which was also used to measure the depth and width of the scored grooves. The system was set to a resolution of 6.4 μm in the lateral and 2.5 μm in the vertical direction.

4. Results

After correcting the CNC-program with the measured contour path, the second step, the scoring process, was performed.

The resulting average depth was $d_{gr} = 250 \mu\text{m}$ for a programmed $a_{e,s} = 100 \mu\text{m}$ and $d_{gr} = 450 \mu\text{m}$ for $a_{e,s} = 300 \mu\text{m}$. The error results from the referencing of the tool to the workpiece. The groove with an average depth $d_{gr} = 450 \mu\text{m}$ shows an average width of 1.568 mm with a standard deviation of 22 μm . The width was measured at 15 sections along a path of 810 mm length with the micro-coordinate measurement system. The resolution was set to 2.16 μm in the vertical direction (height) and 4.91 μm in the lateral direction.

It has been proven in milling experiments (Fig. 6) at a fibre orientation angle of $\phi = 135^\circ$ with rounded cutting edge radii $r_n = 25 \mu\text{m}$ and $r_n = 55 \mu\text{m}$ that fibre protrusions occur if the surface is not scored. Only for a sharp milling tool ($r_n = 7 \mu\text{m}$) no delamination occurred.

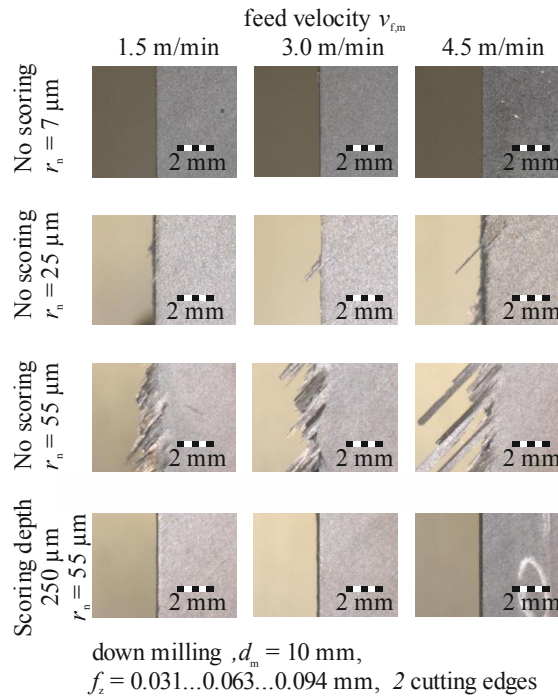


Fig. 6. Quality results with/without pre-milling scoring

The occurrence of protrusions and delamination and their dependence on feed velocity and tool wear was investigated (Fig. 7). Increased feed velocity $v_{f,m}$ and rounded cutting edge radius r_n lead to increasing forces for scored and un-scored samples. Simultaneously, protrusion and delamination on un-scored samples rise. Scored samples do not show any delamination.

There is no significant reduction in the active force for different scoring depths as the workpiece thickness decreases only marginal due to scoring (0.1 – 0.3 % of total

material removal). Measured forces for the scoring process were below 2 N, so they were neglected.

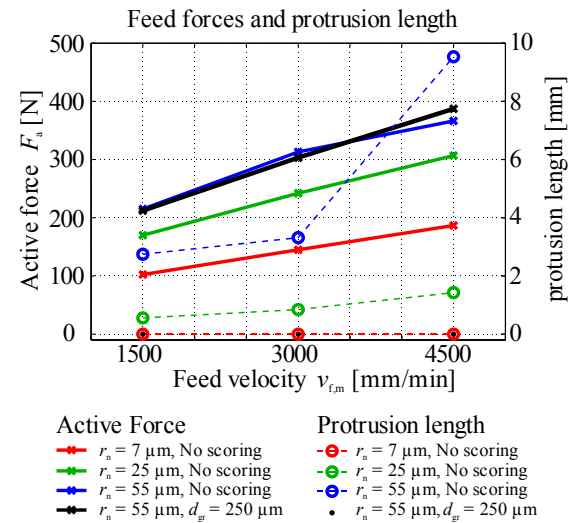


Fig. 7. Active forces F_a of the milling process and resulting delamination depth

When the engagement of the grinding tool is small, scoring it not restricted to straight contours. The minimal radius of the scored contour is defined by the diameter of the grinding tool and its engaging volume. When milling circular holes of 50 mm diameter in un-scored top layers with worn tools ($r_n \approx 55 \mu\text{m}$), delamination and protrusions occur predominantly in the critical range of fibre cutting angles $90^\circ < \Theta < 180^\circ$ (Fig. 8A). The feed velocity $v_{f,m}$ was set to 3 m/min at a cutting velocity $v_{c,m}$ of 754 m/min. Using the same parameters on a pre-scored sample does not lead to delamination of the top layer (Fig. 8B).

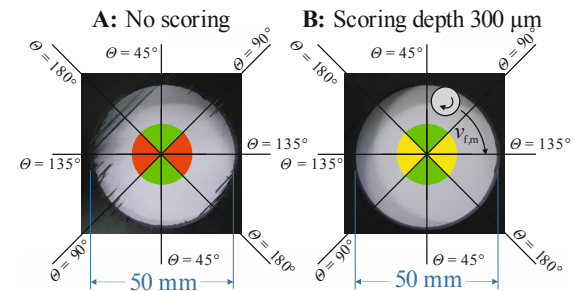


Fig. 8. Milling of circular holes in un-scored and pre-scored top layers

A 3D measurement and the exact profile of a scored, machined workpiece edge is shown in Fig. 9A. The measured volume was $x = 2.2 \text{ mm}$, $y = 2.7 \text{ mm}$ and $z = 1.6 \text{ mm}$. The resolution was set to 2.16 μm in the vertical direction (height) and 4.91 μm in the lateral direction. The graph (Fig. 9B) shows the average height in the x-direction measured from point 0 to 1 starting with the machined face that is followed by the edge and the top layer. At the edge a chamfer of length 0.1 mm an angle of

45° is present, which can be varied and defined by the scoring process and the tool's geometry.

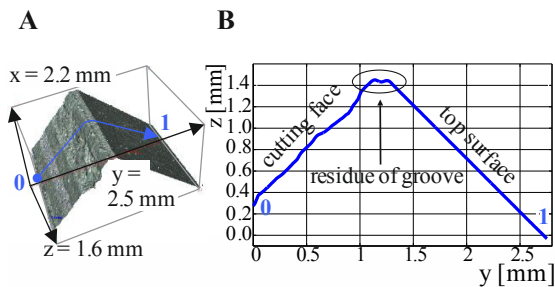


Fig. 9. 3D Measurement and height profile of a machined workpiece edge

In addition to the occurrence and propagation of protrusions and delamination it has to be shown that the depth of an occurring delamination is smaller than the depth of the scored slot. In un-scored areas delamination depth d_d was measured. For the used material it was about 200 μm and therefore not larger than the scored grooves.

5. Summary and Outlook

This paper presents a method to prevent delamination and fibre protrusion of the top layer of FRP components. The conventional milling process of FRP components is extended by a measurement and scoring process prior to milling. The machined groove of the scoring process interrupts delamination propagation, decreases forces on the outermost layer and simultaneously supports workpiece edges. With the presented process combination the following improvements are achieved:

- Prevention of delamination
- Increased tool life due to lower sensitivity to tool wear
- Lowering of machining time due to increased feed velocity

Compared to existing processes the CFRP samples require no rework or protective top layers.

Of course the presented method is affective on the scored surface, only. For delamination-free workpiece edges on the opposing, un-scored surface, a tool with positive back rake angle should be used generating a passive force pointing towards this surface.

A grinding tool with a smaller angle α may be used to avoid the large dependence of the depth of the groove on its width.

By integrating the profile measuring process with the scoring step, the machining time may be further decreased. Alternatively a calibrated optical distance measuring system may be used to increase the maximal measuring feed rate and avoid wear of the measuring system's tip.

This paper presented the basic idea of a pre-milling scoring process, however further research is necessary. Especially the influences of tool wear, cutting and feed velocity on the depth of delamination d_d , should be

investigated in detail to prevent delamination propagation below the scored groove.

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